

# **Boundary Current and Mixing Processes in The High Latitude Oceans**

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## **LONG-TERM GOALS**

This project's overarching goal has been to quantitatively expand our understanding of turbulent mixing, those processes that control it, and its impacts, in those high latitude regions of the global ocean where dense water is formed and sinks to the deep basins. The interest in high latitudes reflects their function as primary source regions for the deep waters that drive the meridional overturning circulation (MOC), a primary component of the mean global ocean circulation. The emphasis on boundaries reflects a concentration at or near boundaries of those processes responsible for deep water formation and initial subduction. Despite the importance of quantifying and better understanding those processes, including mixing, that impact the supply of deep and bottom water to the global ocean, these remote areas remain data-poor and not well understood in comparison with other oceanic regions. As this project has evolved, it has narrowed its focus to the Antarctic zone of the Southern Ocean and its role in formation of Antarctic Bottom Water. The Antarctic zone is taken here to mean the region between the southern edge of the Antarctic Circumpolar Current and the Antarctic continental margins. Processes in this region provide excellent, and in some cases extreme, examples of mixing-related phenomena that are active throughout the world oceans and can significantly broaden our parameter spectrum related to such phenomena. Improved understanding of these processes, which typically have length scales well below the grid sizes used in present-day coupled global ocean climate models (GCMs), can lead to improved parameterizations of the processes in GCMs, enabling them to better represent high latitude processes that drive the MOC.

## **OBJECTIVES**

Work towards this goal has focused on the following objectives:

- Document deep, high latitude boundary currents and dense outflows and the associated mixing processes, and assess the impacts of these processes on water mass modification;
- Document and quantify the generation at high latitude ocean boundaries of mixing-related, small-scale features such as tidally-driven internal waves and intrusive interleaving, and assess their dynamics and impact on adjacent basin waters;
- Acquire quantitative, field-based information on seawater equation-of-state processes, such as double-diffusion, cabbeling and thermobaric instability, that are anticipated to play significant roles at high latitudes where temperatures are low and static stability is frequently weak; and,
- Actively coordinate, through participation in working groups and conferences, results from these efforts with those being obtained through field efforts elsewhere in the global ocean and with parallel modeling efforts.

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## APPROACH

This research, initially based primarily on collection and analyses of field data, has evolved to a stage where numerical modeling carried out by collaborators is used in conjunction with field results to better understand the dominant processes. Field data are used to describe physical systems, and generate or improve conceptual models that are used in turn to structure suitable laboratory and numerical modeling approaches. The field data are then used to parameterize the models and to validate the output. The model results are used to aid in assessing pertinent dynamic processes and in interpreting the field results. Models can also be useful for interpolating data over spatial and temporal scales that are important within a process context but that can be very difficult to adequately sample in the field.

Field work has been carried out from research platforms made available through programs funded by both US and non-US organizations, allowing access to resources that would otherwise have been either unavailable or prohibitively costly to this grant. Instrumentation has included conductivity-temperature-depth (CTD) profiling systems, lowered and vessel-mounted acoustic Doppler current profiler (ADCP) systems, and microstructure profilers including a CTD-mounted scalar microstructure profiling system (CMiPS) and a free-falling, tethered scalar and shear microstructure profiler (VMP). Time series data have been acquired from moored instruments. Study sites were selected, based on the likely occurrence of deep-water formation, modification through mixing, and transport to the deep ocean, in the Weddell and Ross seas. These two regions contribute ~75% of the Antarctic Bottom Water to the global ocean [Orsi *et al.*, 1999] and contain highly suitable sites for studies addressing the above listed goals.

Quantitative information on mixing is derived from field data using documented methods. The techniques derived by *Osborn and Cox* [1972] and *Osborn* [1980] are used as the basis for deriving mixing-related parameters from scalar and shear microstructure data. Vertical current profiles measured by vessel-mounted or lowered ADCPs have been used in conjunction with CTD data to estimate mixing under certain conditions [Polzin *et al.*, 2002]. We apply diverse methods under different physical situations, and the results are intercompared where possible in order to investigate the limitations of each method under conditions varying from extremely quiescent (e.g., double-diffusive) to very energetic (e.g., dense outflow with shear-driven instabilities) conditions.

Present collaborators include *Mike Dinniman* and *John Klinck* (Old Dominion Univ.), *Arnold Gordon* (Columbia Univ.), *Robert Hallberg* (NOAA/GFDL), *Alejandro Orsi* (Texas A&M Univ.), *Tamay Ozgokmen* (Univ. of Miami), *Laurence Padman* (Earth & Space Research), and *Anna Wåhlin* (Göteborg University).

## WORK COMPLETED

Specific accomplishments include:

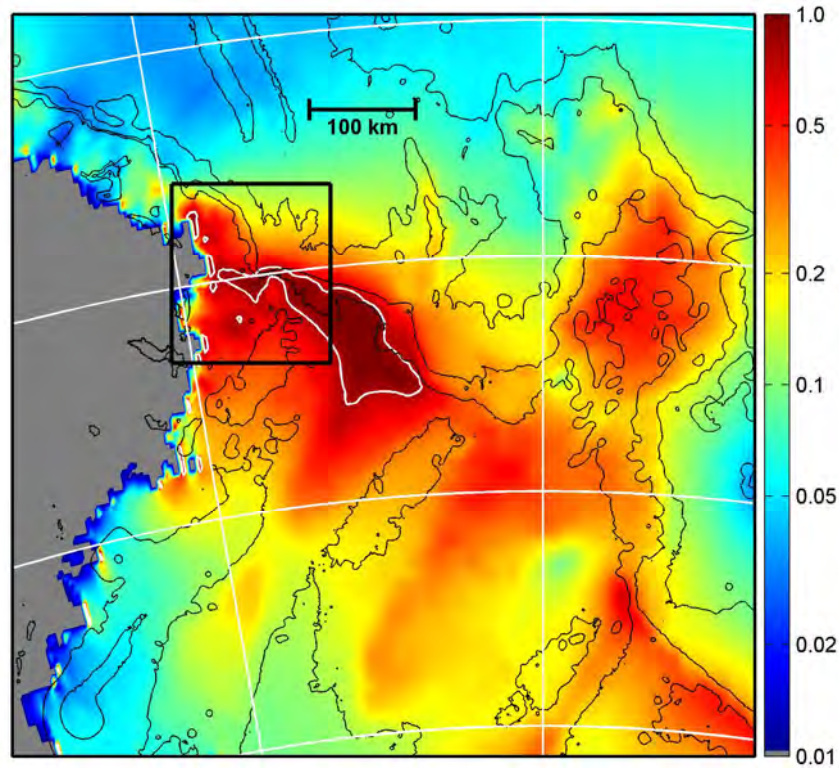
- Completed an assessment of the contribution of strong local tides to mixing and evolution of the bottom-trapped, dense outflow from the NW Ross Sea (invited presentation at the May 2007 Liège Colloquium on Ocean Mixing, with manuscript submitted to the proceedings volume [Muench *et al.*, 2008a]).

- Initiated new collaborative analyses of existing field data using laboratory model results in concert with numerical models to assess the influence of downslope corrugations, superimposed on a very steeply sloped seafloor, on the evolution of the NW Ross Sea outflow (preliminary results submitted for presentation at the March 2008 Ocean Sciences meeting [Muench *et al.*, 2008b]).
- Developed early results from a unique field dataset including scalar and shear microstructure data from an actively freezing Antarctic coastal polynya: the Mertz Glacier Polynya, one of three primary sources for Antarctic Bottom Water (presented at the 2006 Fall AGU meeting [Muench *et al.*, 2006a]).
- Completed a field and modeling study of interactions among mean regional circulation, the topography of the Maud Rise region in the eastern Weddell Sea, and the mesoscale features that arise through these interactions [de Steur *et al.*, 2007].
- Completed an analysis describing physical oceanographic conditions and diapycnal mixing in the western Weddell Sea boundary region, the site for primary dense water outflow from the Weddell Sea [Absy *et al.*, 2008].
- Continued as chair of IAPSO/SCOR Working Group 121 on Ocean Mixing; co-chair for an ocean mixing session at the Fall 2006 AGU meeting in San Francisco; lead convenor of an ocean mixing symposium at the July 2007 IAPSO (International Association for Physical Sciences of the Ocean) Assembly in Perugia, Italy; and organization, as chair, of an ocean mixing session scheduled for the March 2008 Ocean Sciences Meeting in Orlando, Florida. Preparation has been started on an overview of ocean mixing, intended as a final report for SCOR Working Group 121, which will be submitted to The Oceanography Society magazine for 2008 publication.

## RESULTS

**Ross Sea: Dynamics and Mixing of a Dense Outflow in the NW Ross Sea.** Hydrographic, current and microstructure data obtained during 2003-2005 from the northwestern Ross Sea have been used, in conjunction with results from a regional barotropic tidal model [Erofeeva *et al.*, 2005], to estimate the impacts of strong regional tidal currents on the evolution of a bottom-trapped dense outflow from the Drygalski Trough (Fig. 1). This outflow, with an estimated mean transport approaching 2 Sv [Gordon *et al.*, 2004; Whitworth and Orsi, 2006], supplies a significant percentage of global Antarctic Bottom Water. It also provides an example of outflow behavior over an unusually steep continental slope (slopes vary from  $\sim 1:10$  to  $\sim 1:6$ ) that is cut with downslope corrugations (Fig. 2) and impacted by primarily barotropic tidal currents that can exceed  $1 \text{ m s}^{-1}$  (Fig. 1). Maximum downslope outflow speeds that approached  $1 \text{ m s}^{-1}$  on the steep upper slope led to interfacial Froude numbers  $Fr > 1$ , reflecting highly turbulent flow that contributed to an entrainment velocity  $w_e$  as high as  $1\text{-}4 \times 10^{-3} \text{ m s}^{-1}$  ( $100\text{-}400 \text{ m day}^{-1}$ ). The combination of high outflow and tidal current speeds contributed to interfacial and benthic stresses each of order  $\sim 1 \text{ Pa}$ . Vertical eddy diffusivity across the interface, computed from scalar microstructure profiles, was  $K_z \approx 0.004 \text{ m}^2 \text{ s}^{-1}$ , with a corresponding downward heat flux  $F_h \approx 10^3 \text{ W m}^{-2}$ . Estimates using simple scaling arguments show that tidal currents during the spring portion of a dominant fortnightly cycle increase the mean benthic stress opposing the outflow by a factor of  $\sim 2\text{-}3$  relative to the neap case, thereby thickening the bottom Ekman layer and significantly enhancing downslope transport. These results have been submitted for publication [Muench *et al.*, 2008a], and are being presented and discussed within the context of dense outflow parameterization at a November 2007 meeting of the CLIVAR Gravity Current Entrainment Climate Process Team.

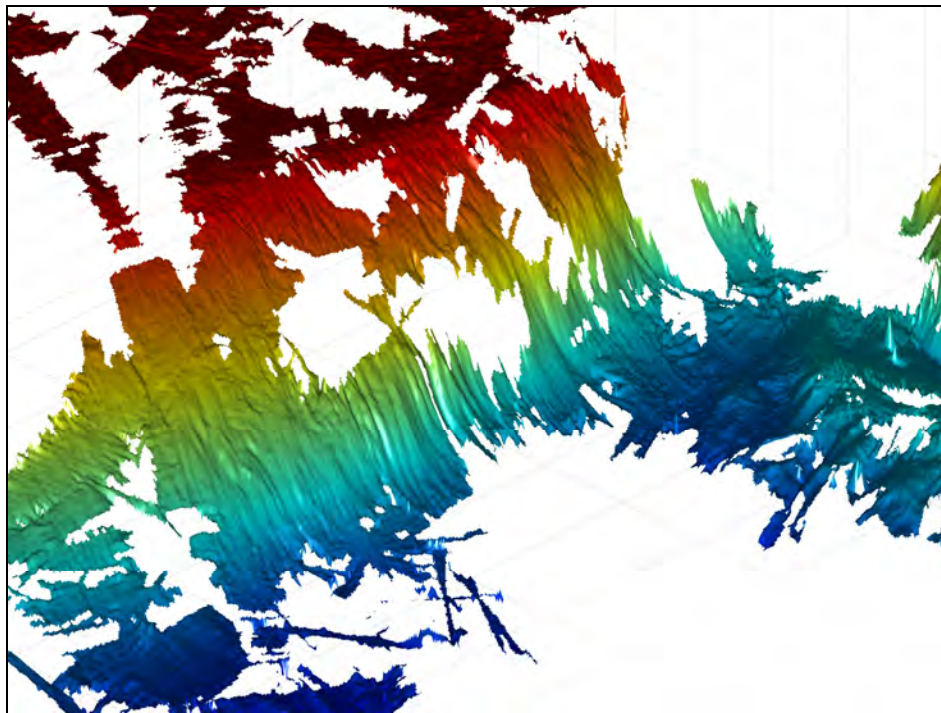
The corrugations on the steep slope down which the dense outflow from Drygalski Trough descends extend from the shelf break down to ~2000 m and are of order ~1 km wide and 5-20 m in depth (Fig. 2, and see *Davey and Jacobs* [2007]). *Wåhlin* [2004] suggested that flow over similar corrugations on the East Greenland continental slope can have a significant impact on the outflow pathway. A collaborative group has been formed, consequent to discussions held at the May 2007 Liège Colloquium on Ocean Mixing, with the intent to analyze the existing field data using a combination of existing results [e.g. *Wåhlin*, 2004; *Darelius and Wåhlin*, 2007] and new model runs.



**Figure 1. Maximum tidal current speed ( $u_{max}$ ) from Ross Sea barotropic tide inverse model [Erofeeva et al., 2005]. Color scale ( $m s^{-1}$ ) on right is logarithmic. White contour shows  $u_{max} > 0.8 m s^{-1}$ . Black contours show 530, 1000, 2000 and 3000 m isobaths. Black rectangle outlines the Drygalski Trough sill region.**

Preliminary discussion has suggested that the corrugations might tend to steer at least the lower part of a thick outflow and perhaps the greater part of a thinner outflow toward a more downslope direction. Such an effect might help to explain *Gordon et al.*'s [2004] observation, based on LADCP current records, that the outflow trended ~35° downslope from the isobaths as compared with the more typical trend of ~10° [see e.g. *Killworth*, 1977]. *Gordon et al.* [2004] also noted, based on time series current and temperature data obtained from a mooring on the upper slope off Drygalski Trough, that downslope flow events tended to occur during the transition to spring tides. Such events may reflect interactions among cross-slope tidal excursion, the corrugations, and the thermobaric effect that would tend to increase outflow density as it flowed downslope. Such events represent “shortcuts” of the normal dense outflow trajectory and can be expected to impact outflow mixing, hence, the hydrographic characteristics of the resultant bottom water. The corrugations likely impact benthic stress, inasmuch as along-isobath flow (across the corrugations) would “feel” a greater bottom

roughness (in the sense of form drag) than flow directly downslope paralleling the corrugations. A simple scaling analysis presented by Wåhlin [2004] suggests, when applied to the present case, a dynamical linkage involving the slope gradient, the width scales of the corrugations, and the outflow thickness. These issues are being investigated in greater depth, and preliminary results will be presented at the March 2007 Ocean Sciences Meeting [Muench *et al.*, 2008b].



*Figure 2. 3-D image, derived from unpublished high-resolution multibeam (“swath”) data, showing seafloor corrugations oriented downslope on the NW Ross Sea continental slope. View is toward the shelf, depths varying from ~500 m (dark red) to >3000 m (dark blue). Along-slope view is ~50 km in extent.*

**Mixing in the Mertz Glacier Polynya in Winter.** While work in the Ross Sea has focused on the dense outflow, the first-ever scalar and shear microstructure observations from an active Antarctic coastal polynya were acquired during austral winter 2004. This polynya, the Mertz Glacier Polynya, is a primary formation site for cold, saline, dense water that may contribute as much as 25% of the Antarctic Bottom Water in the global ocean [Rintoul, 1998]. These data have provided a rare opportunity to examine diapycnal mixing processes associated with initial densification of water that will later mix with Lower Circumpolar Deep Water to form Antarctic Bottom Water. The observations were obtained during the relaxation period following a cold ( $-21^{\circ}\text{C}$ ), energetic ( $>25 \text{ m s}^{-1}$ ) offshore katabatic wind event during which salinity increase in the ~400 thick mixed layer was consistent with ~6 cm of new ice growth. Dissipation values in the upper 300 m of this layer remained high, with  $\epsilon > 10^{-7} \text{ m}^2 \text{ s}^{-3}$  for at least 5 hours following cessation of the wind event. Persistence of mixing after relaxation of the wind forcing indicates that processes occurring during this phase need to be included in models of polynya response in order to adequately represent the contribution of such polynyas to dense water formation in GCMs. Preliminary results of this work in progress were presented at the 2006 Fall AGU meeting [Muench *et al.*, 2006a].

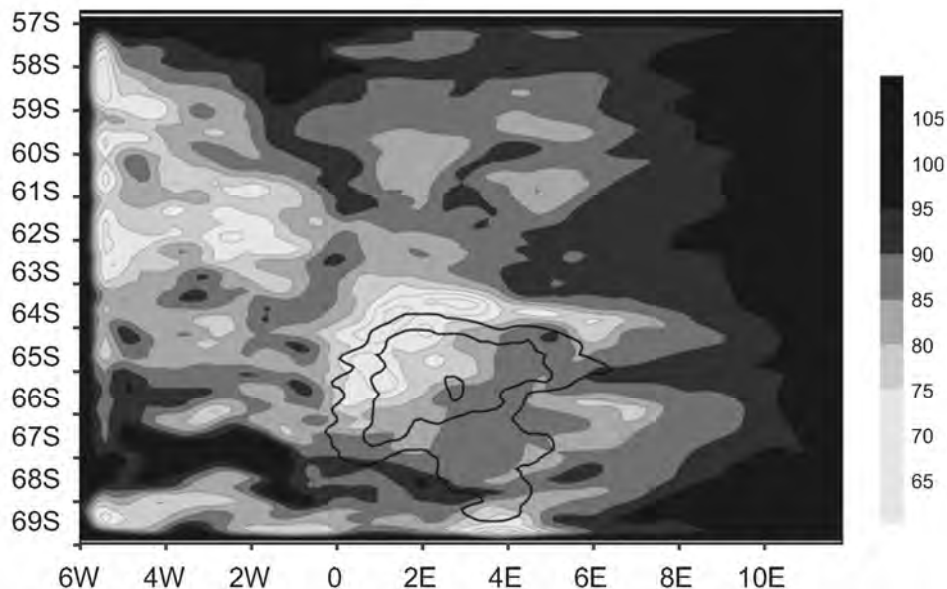


**Weddell Sea: Open Ocean Deep Convection and Ocean/ice Interactions.** The NW Ross Sea remains the primary research site for this project; however, the southwestern and western Weddell Sea also contains sites for bottom water formation [e.g., *Foldvik et al.*, 2004; Gordon, 1998]. Further, deep convection leading to bottom water cooling has occurred in the region immediately surrounding Maud Rise Seamount in the eastern Weddell Sea [Gordon, 1978]. The Maud Rise region is overlain in winter by pack ice that is perennially thinner than over the surrounding ocean and is, at times, completely absent. Field data obtained from the region during the 2005 MaudNESS program revealed conditions similar to those observed in the past [e.g., Gordon, 1978; Muench *et al.*, 2001], with a mid-depth warm annulus surrounding the Rise and overlain by a reduced mixed layer depth. Resulting availability of a shallow oceanic heat source opens the possibility that storm-forced upper layer mixing can erode the thermocline and further diminish the already weak vertical stratification. This weak stratification is consistent with a diapycnal cabbeling control over mixing between the surface mixed layer and the warmer deep water. Should significant winter ice formation occur, releasing brine to the surface layer, the cabbeling limit can be approached. At that time double-diffusive-like steps form, upward heat flux increases and warms the surface mixed layer. This in turn melts ice, reduces salinity and moves the system away from the cabbeling limit. Preliminary results based on scalar and shear microstructure profiles show small step-like features that are consistent with occurrence of cabbeling.

The 2005 field data provided much more complete coverage of the Rise than previously available. A subsequent integrated mesoscale field and modeling effort has shown that presence of the warm annulus and associated shoaling depends upon impingement of the regional southwestward flow onto the Rise [*de Steur et al.*, 2007]. The warm annulus originates as Upper Circumpolar Deep Water that flows southwestward into the eastern Weddell Sea and impinges on the topography associated with the Rise, which is order 200 km across and rises from a 4000 m seafloor to summit depths < 2000 m. Model results, which compare well with the field observations, show that regional flow impinging on the Rise bifurcates, with most continuing westward along the northern flank. Cyclonic and anticyclonic eddies form during this flow past the Rise, then continue westward after separating from the flanks of the Rise (Fig. 3). The eddies are dominated by cyclones, which adhere to the Rise more strongly than anticyclones. Model results predict, and satellite altimetry data show, formation of 3-5 eddies per year through this mechanism. Averaged over time, presence of the eddies accounts for the halo and its accompanying shoaled pycnocline. The model was run using different parameter combinations and reveals that, in the event that the relatively slow mean flow ( $\sim 0.03\text{-}0.05 \text{ m s}^{-1}$ ) west-southwestward past Maud Rise were to increase, eddy formation rate can increase dramatically. For a mean flow of  $0.15 \text{ m s}^{-1}$ , virtually the entire surface mixed layer overlying the Rise thins to less than 40 m, leading to a correspondingly increased opportunity for thermocline erosion, weakened vertical stratification and diapycnal mixing through processes that derive from the seawater equation of state. The entire region comprises a natural laboratory for study of these processes, which are not well documented in the field. They can play significant roles, especially in low energy oceanic regions, and knowledge gained through the ongoing analyses will contribute to our ability to represent them in large-scale models.

**Weddell Sea: Diapycnal Mixing Along the Continental Shelf.** Analyses of hydrographic conditions and diapycnal mixing based on field data obtained during late winter 2004-2005 along the western Weddell Sea slope have been completed [*Absy et al.*, 2008]. Intercomparison with conditions observed a decade earlier reveal a decrease in salinity of the permanent pycnocline. Further, the robust deep dense outflow that originates in the southwestern Weddell Sea [*Foldvik et al.*, 2004], and that was observed in 1992, was colder and patchier in 2004-2005. The typical regional mean northward, barotropic currents, while present, were considerably weaker. Heat fluxes through the pycnocline were

in the  $3\text{--}5\text{ W m}^{-2}$  range and reflected both double-diffusive convection and weak shear-driven instabilities. A limited number of observations revealed shear-driven instabilities associated with intrusions and with the upper interface of the patchy, bottom-trapped dense outflow. Vertical diffusivities associated with these instabilities fell typically in the range  $K_z \approx 10^{-4}$  to  $10^{-3}\text{ m}^2\text{ s}^{-1}$ . The larger values in these ranges were associated with the upper slope, and this can presumably be attributed to strengthening tidal currents upward toward the shelf break as reported by *Levine et al.* [1997], and similar to the Ross Sea case. Insight gained into the processes contributing to mixing (double diffusion, shear-driven instabilities and the possible impact of tidal variability across the slope) are anticipated to be of use in parameterizing this and other boundary regions within GCMs.



**Figure 3.** *Upper mixed layer thickness (m) surrounding Maud Rise seamount (18-month run, 11 layers,  $0.05\text{ m s}^{-1}$  westward regional flow). Shoaled mixed layer areas reflect generation, shedding and westward migration of mesoscale eddies [de Steur et al., 2007].*

## IMPACT/APPLICATIONS

The research reported above has immediate applications with respect to parameterization of mixing in large-scale ocean models, and reflects recommendations recently published by IAPSO/SCOR Working Group 121 on Ocean Mixing [*Muench et al.*, 2006b]. It addresses dynamics that couple small- and microscale processes, that can be related quantitatively to mixing, with forcing at larger scales. Results on the Ross Sea dense outflow specifically apply to a major issue with global ocean modeling: the difficulty with adequately incorporating relatively small-scale dense overflows, which are essential to the meridional overturning circulation, into global scale models.

This research has involved derivation of mixing parameters using a variety of data types including CTD-derived finestructure profiles, vertical current profiles, and scalar and shear microstructure profiles. Intercomparison of these methods and of the conditions under which each is appropriate, coupled with attempts to develop user-friendly methods, are part of an ongoing attempt to entrain interested non-specialists into the “ocean mixing” community. The hope is that this can encourage



acquisition of mixing data sufficiently to, over time, construct a global scale “ocean mixing climatology” that will contribute to our understanding of the advective-diffusive balance that constrains the large-scale circulation.

## RELATED PROJECTS

The following projects are closely related topically to results reported above and have contributed data for use in deriving the results. Unless noted otherwise, funding for research platforms and instrumentation has been provided through the US National Science Foundation.

**The Antarctic Slope study (AnSlope)** [Gordon *et al.*, 2004] seeks to assess slope processes and their impacts on local water modification, cross-shelf transport and on the dense outflow from the Ross Sea. Underway analyses attempt to identify and quantify the dynamic processes responsible for regional diapycnal mixing, and the impact of this mixing on larger-scale processes.

**The Maud Rise Nonlinear Equation of State Study (MaudNESS)** [de Steur *et al.*, 2007] seeks to quantify and to better constrain, through analyses of small-scale and microstructure observations in the very weakly stratified eastern Weddell Sea, seawater equation of state-related processes such as cabbeling, double diffusion and thermobaricity.

**Ice Station Polarstern (ISPOL)** [Hellmer *et al.*, 2006] was a late winter cruise to the western Weddell Sea that acquired hydrographic, current and scalar microstructure data adequate to assess the water column along the western margin, including the dense outflow, and to compare hydrographic and mixing conditions with those observed in 1992. Field expenses were borne by the Alfred-Wegener-Institute for Polar and Marine Research, Bremerhaven, Germany.

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